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Salinization of freshwater aquifers due to subsurface fluid injection quantified by species transport simulations

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Abstract

Potable groundwater resources could be affected by salinization as result of subsurface utilization like CO_2 injection. We examine the potential of freshwater impairment for shallow aquifers and a drinking water well due to upward displacement of saline formation water along an erosional channel and a fault for a prospective storage site in the Northeast German Basin. Location and degree of salinization is governed by the hydrogeological properties of the migration pathways, while the initial local groundwater flow has only a minor impact. Moreover, an early warning is possible within the time frame of a few months.

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Keywords: shallow aquifer; erosion channel; fault; brine displacement; early warning; drinking water well

1. Introduction

The quality of potable groundwater is of high importance for freshwater resources, especially in regions where the vast bulk of drinking water is gained from groundwater, as in the study area where this concerns 99% of the drinking water [1]. Subsurface activities like CO_2 injection could lead to salinization of shallow groundwater resources due to upwards displaced saline formation water along permeable migration pathways. Therefore it is

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crucial to investigate the main influencing factors on distribution of salinization as well as to determine if and in which time frame early warning is possible. Our study is based on the work of Tillner et al. [2,3] who investigated the influence of permeable fault systems on brine displacement for the prospective storage site Beeskow-Birkholz in the Northeast German Basin. With a 3D regional scale model considering the saline groundwater system, they demonstrated that the existence of hydraulically conductive faults is not necessarily an exclusion criterion for potential injection sites, because salinization of shallower aquifers strongly depended on the effective damage zone volume, the initial salinity distribution and overlying reservoirs [2], while permeability of fault zones did not influence salinization of shallower aquifers significantly [3].

Here, 2D species transport simulations are used to examine salinization of the shallow freshwater system due to inflow of saline water through a fault at the base of the model. This is of particular relevance because within the study area an initial geogenic salinization above the salt-freshwater interface is present already [4] and a fault zone as well as an erosional channel exists, representing both potential pathways for upward brine migration. The intrusion rates of saline formation water as well as the permeability of the fault are varied. Also, the influence of the regional groundwater flow and an active drinking water well on the salinization potential of the shallow freshwater aquifers is examined. Hence, for different hypothetical monitoring wells the time frame is determined within which early warning of freshwater impairment is feasible for the study area and if it is possible before extensive salinization arise.

2. Study area, model set up and investigated scenarios

2.1. Study area

The prospective storage site Beeskow-Birkholz is located 80 km SE of Berlin in the Northeast German Basin (NEGB), see Fig. 1a. The storage formation within Middle Buntsandstein, where it was planned to inject 35 Mt CO_2 over a period of 20 years, is overlaid by a multi-barrier system consisting of the common sediment successions from the NEGB [5]. These exclusively saline aquifers are separated by a regionally distributed aquitard, the Rupelian clay, from the freshwater bearing layers above (Fig. 1b). The overlying quaternary sediments were particularly formed due to glacial and interglacial periods and are characterized by a frequent change of facies and variations in sediment thickness [1]. Porous layers of sand and gravel forming freshwater aquifers interlayered by aquitards consisting of silt and marly till.

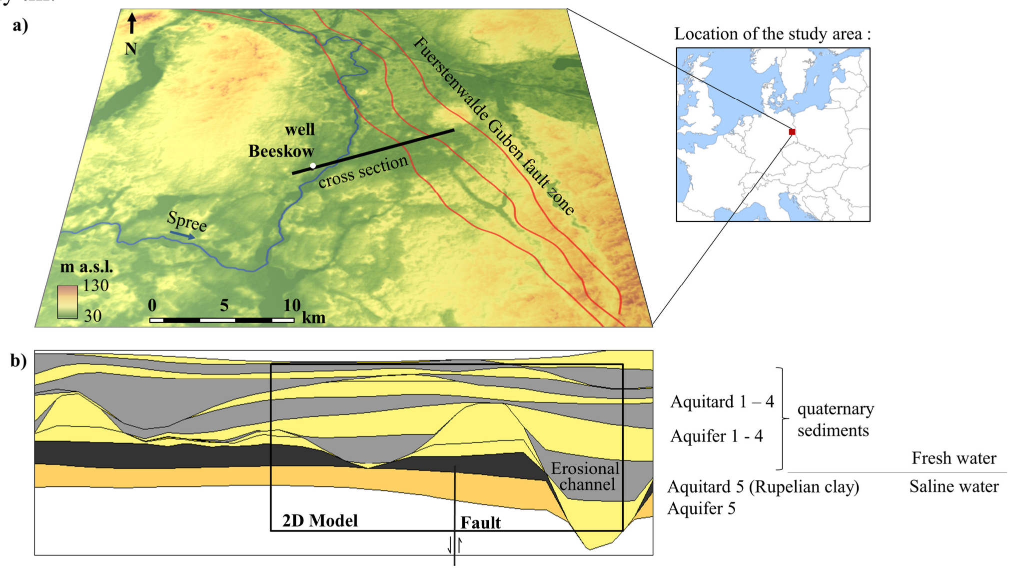


Fig. 1. (a) Overview of the study area displaying the river Spree, the drinking water well Beeskow and the Fuerstenwalde Guben fault zone; (b) the selected cross-section comprise the fault as well as the erosional channel as potential migration pathways.

In some areas, deep reaching channels were formed due to glacial erosional processes, which partially cleared out the Rupelian clay. Further, the Fuerstenwalde Guben fault zone provides in some areas a hydraulic connection also to freshwater aquifers [4]. Both represent feasible migration pathways between shallow and deep groundwater and are responsible for pre-existing local salinization above the regional salt-freshwater interface.

2.2. Model set up

The model is based on hydrogeological cross sections provided by the state office for mining, geology and resources of Brandenburg (LBGR). In Figure 2a the cross section is given with a total length of 11 km and a height of 220 m including five confined aquifers as well as aquitards. Porosity and permeability values are defined based on material properties of the sediments according to DIN 18130 [6], see Fig. 2a.

For the density dependent species transport simulations the program code SHEMAT [7] is used. Three different water types with different salt concentrations are implemented according to the regional hydrochemical model after Rechlin [8], which categorizes shallow groundwater by the main ion ratios of their dissolved components and associates them with a certain location within the Valjashko [9] diagram (Fig. 2b). The model has been applied already for early warning of saltwater intrusions within freshwater aquifers and surface water in the state of Brandenburg [10,11]. In the shallowest layers within the 2D model the so called matured recharge type can be found, while the stationary groundwater type occurs in deeper aquifers with longer residence time. Both are implemented with constant concentrations of 0.5 g/L and 1 g/L total dissolved solids, respectively. Further, there exists an initial salinization above the regional aquitard: salinity is assumed to increase gradually up to 25 g/L with highest concentrations close to the fault and the erosional channel, declining with increasing distance [4].

Open boundary conditions are applied for the lateral flow, implemented by constant hydraulic heads. It is assumed that the saline water flows from the fault into aquifer 5 (Fig. 2b) with a constant concentration of 25 g/L. The inflow rates are based on previous simulations of Tillner et al. [2], who simulated injection-induced brine displacement within the deep groundwater complex towards aquifer 5. The study area comprises also the river Spree and the active drinking water well Beeskow.

Within the baseline scenarios just described, inflow is considered only across the fault. Further scenarios investigate the influence of the regional groundwater flow on the salinization by implementing hydraulic heads from the groundwater contour plan [4]. Therefore lateral flow boundaries as well as the river were taken into account with open boundary conditions. The initial flow velocities range from maximum 11 m/a in the upper aquifers to 3 m/a in the lower aquifer 4. In additional scenarios it is examined if the active drinking water well Beeskow with an extraction rate of $1.5 * 10^{-3}$ m^3/s supports the distribution of the salinization e.g. due to suction of saltwater from lower aquifers.

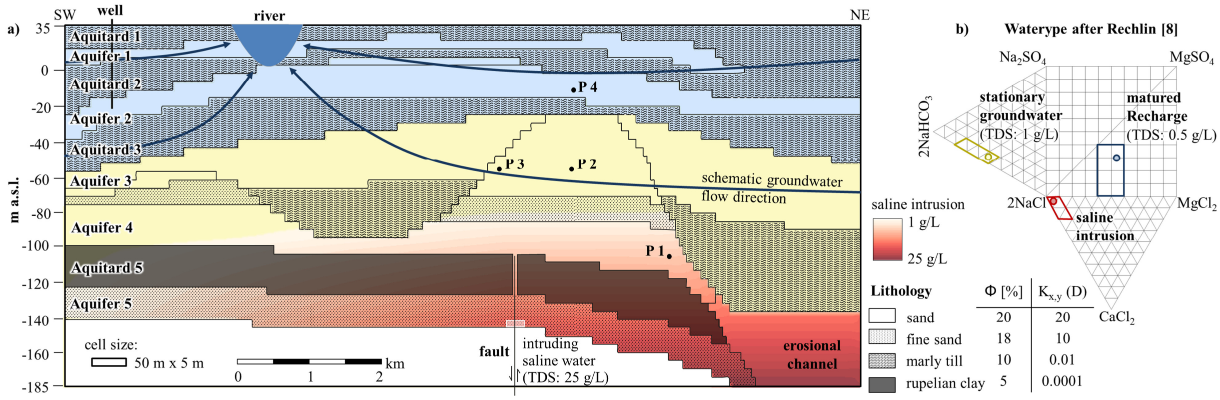


Fig. 2. (a) Cross-section including the lithology and their hydraulic properties as well as the three different groundwater types; (b) Position of the water types after Rechlin [8] (boxes) and their composition (dots) within the Valjashko diagram [9].

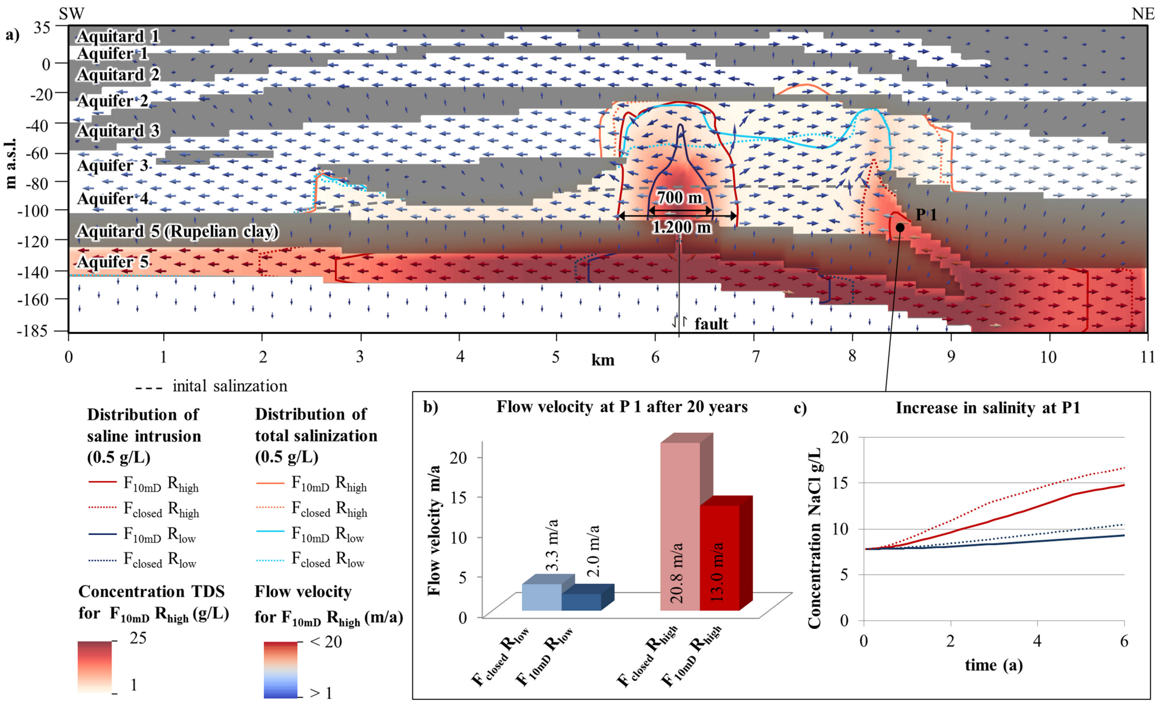


Fig. 3. (a) Resulting flow vectors ($F_{10mD}R_{high}$) and distribution of salinization for different scenarios after 20 years; (b) flow velocity out of the erosional channel, as well as (c) the resulting increase in concentration at monitoring point P1.

3. Results and discussion

3.1. Distribution of freshwater salinization

If fluid flows preferentially through the fault or the erosional channel it is governed by the hydrogeological properties of the migration pathways. Consequently, they control the location and the degree of salinization, as can be seen in Figure 3a. After 20 years a distance of 1.200 m ($F_{10mD}R_{high}$) and 600 m ($F_{10mD}R_{low}$) around the fault is affected by a salinization of more than 0.5 g/L sodium chloride, which roughly represents the regulatory limit for drinking water [12].

Further a permeable fault leads to lower upward displacement along the erosional channel, as emphasized by the reduction in flow velocity of 38% out of the channel (Fig. 3b). However, freshwater salinization arises even if the fault is closed and a lower inflow rate is assumed ($F_{closed}R_{low}$). In this case the flow velocity out of the erosional channel is reduced by 84%, which still leads to an increase in concentration especially close to the channel (Fig. 3c). Within the injection period of 20 years, salinization is only restricted to the interconnected aquifers 3 and 4, as aquitard 3 prevents further upward migration. The initial distribution of saline water within the study site is an important influencing factor on total salinization, since the intruding fluid leads only to a concentration increase close to the migration pathways (Fig. 3a).

Local background groundwater flow has a minor impact on the propagation of saline water. The pre-injection flow velocities near the migration pathways are at maximum 5 m/a and decrease with increasing depth, while the injection-induced fluid flow within the aquifers increases to 1.3 m/a (Fig. 4b). Within the deeper aquifers 3 and 4 fluid flow is dominated by intruding saline water, resulting in low additional transport towards the recharge area. The higher the injection rate, the lower is the influence of the local groundwater flow on saltwater distribution

(Fig. 4a): within aquifer 3 salinization spreads additional 120 m in case of a high intrusion rate (F_{10mD} R_{high} GF), while the saltwater plume is shifted 500 m towards the river when the injection rate is low (F_{10mD} R_{low} GW). However, the total extent of the saline intrusion around the fault does not vary significantly compared to the scenarios not considering the regional groundwater flow. Within the shallower aquifer 2 the local groundwater flow dominates the flow regime, transporting saline water towards the recharge area, while this aquifer was not influenced by salinization before (Fig. 4 a).

The drinking water well Beeskow is not affected by salinization in any scenario. Further, no suction of saline water from lower aquifers can be observed. The well affects mainly the groundwater flow on the other side of the river Spree, while flow velocities near the migration pathways increase by only 0.9 to 5% compared to the simulations considering exclusively the local groundwater flow (Fig. 4b). Consequently, the influence of the well on the distribution of salinity is negligible, as can be seen in Fig. 4a. Nevertheless, the salinization potential of a drinking water well in general depends considerably on its relative position to migration pathways as well as the local hydrogeological situation.

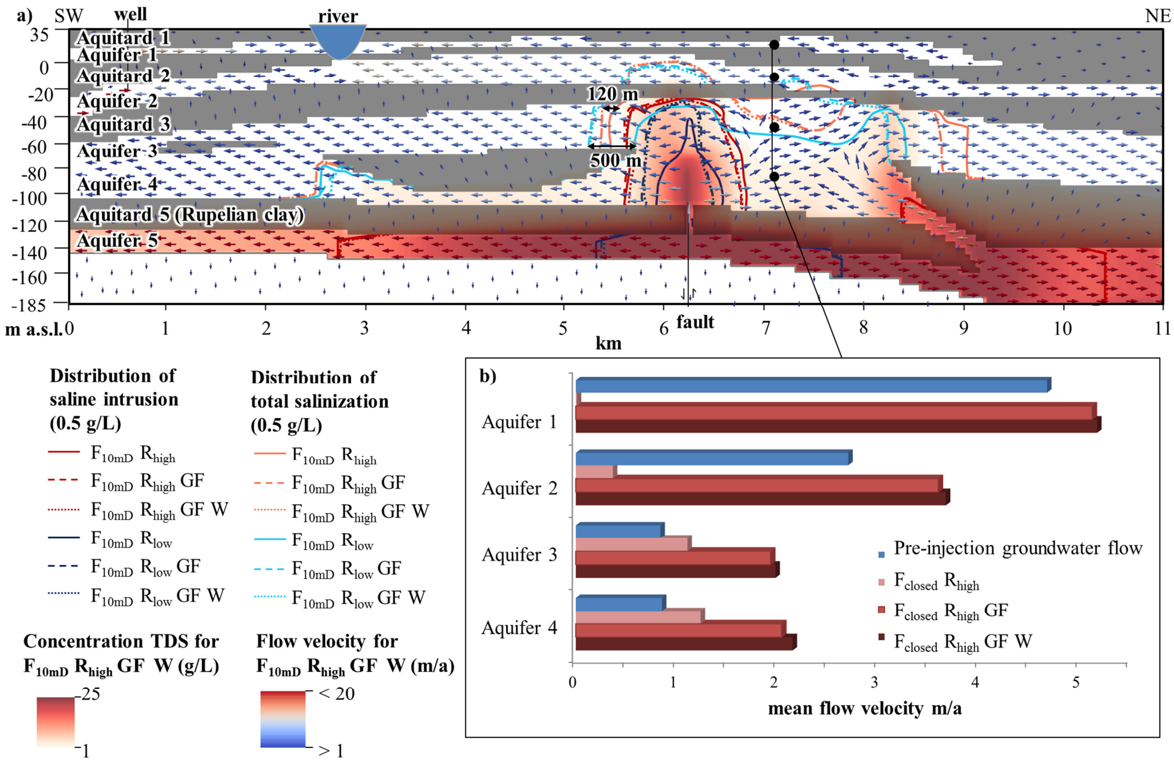


Fig. 4. (a) Resulting flow vectors ($F_{10mD}R_{high}$GF) and distribution of salinization after 20 years considering local groundwater flow as well as an active drinking water well; (b) mean flow velocities for aquifer 1 to 4 along the profile (black dots) near the migration pathways.

Table 1.Overview of all calculated scenarios as well as the time when salinity increases locally by more than 0.1 g/L sodium chloride at different monitoring points (Fig. 2a)

Scenario	Fault permeability [mD]	Intrusion rate [m^3/s]	t* at P1 [a] erosional channel	t* at P2 [a] between two migration pathways	t* at P3 [a] fault zone	t* at P4 [a] aquifer 2
$F_{closed}R_{high}$	as host rock (0.01)	$3.4 * 10^{-3}$	0.3	0.96	1.05	16.9
$F_{closed}R_{high}$ GF			0.3	0.49	0.64	6.2
$F_{closed}R_{high}$ GF W			0.29	0.47	0.61	6.1
F_{10mD} R_{high}	10		0.43	0.86	0.53	9.5
F_{10mD} R_{high} GF			0.42	4.23	0.39	13.3
F_{10mD} R_{high} GF W			0.41	4.85	0.35	14.3
$F_{closed}R_{low}$	as host rock (0.01)	$6.1 * 10^{-4}$	0.95	3.22	3.52	-
$F_{closed}R_{low}$ GF			0.93	1.18	1.35	12.1
$F_{closed}R_{low}$ GF W			0.93	1.12	1.28	11.6
F_{10mD} R_{low}	10		1.34	3.13	1.68	-
F_{10mD} R_{low} GF			1.32	1.98	0.91	17.7
F_{10mD} R_{low} GF W			1.28	1.63	0.69	16.7

*Δc_{NaCl}> 0.1 g/L; GF – local groundwater flow; W - well

3.2. Early warning about salinization

A saline intrusion can be monitored near potential migration pathways by increasing sodium chloride concentrations already after a few months since the inflow into aquifer 5 due to the subsurface fluid injection started. At the erosional channel an increase of 0.1 g/L sodium chloride can be observed after 0.3 to 0.43 years in simulations with a high intrusion rate, while it takes more than three times longer for a lower rate (Fig. 5). At monitoring point P3, 300 m SW of the fault, the time frame for detecting the saline intrusion is similar with 0.53 years (F_{10mD} R_{high}, Table 1), provided that the fault is permeable. Considering further the regional groundwater flow increase in salinity can be observed 34% (F_{10mD} R_{high}) up to 59% (F_{10mD} R_{low}) earlier due to higher flow velocities towards the river.

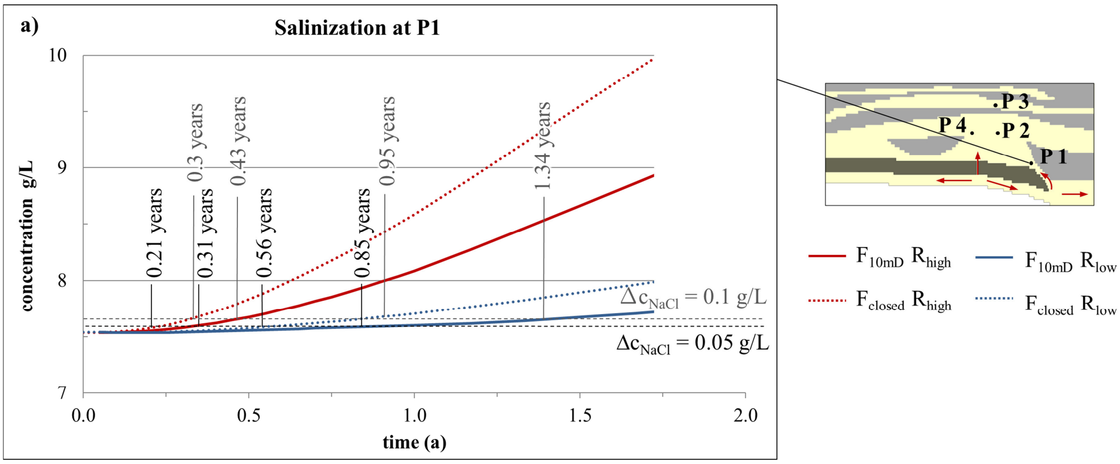
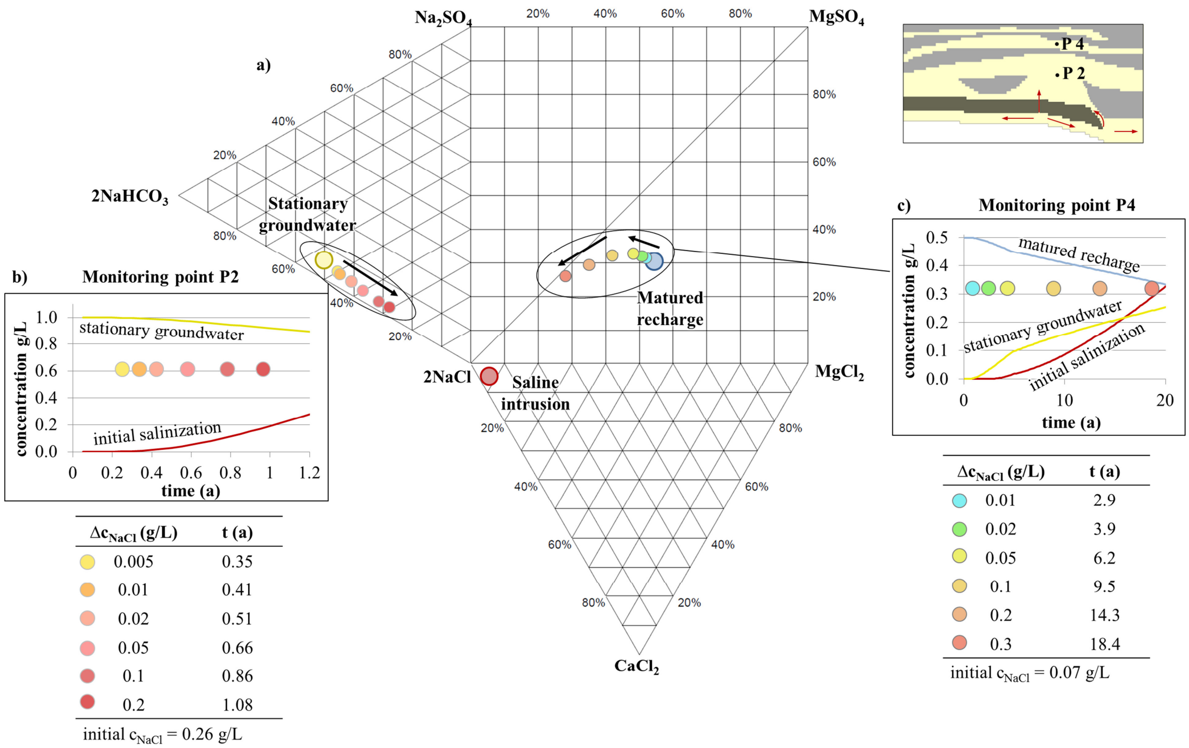


Fig. 5. Salinization increase in the erosional channel. The influence of background groundwater flow is negligible.

However, the position of potential migration pathways is often not exactly known. Table 1 shows that continuous observation in a central part within the affected aquifer 4, one kilometre away from both migration pathways, the time for salinity increase is highly variable due to the flow regime and ranges from 0.49 years (F_{closed} R_{high}) up to 4.85 years (F_{10mD} R_{high}). Hence, it is recommendable to have several observation wells to detect freshwater impairment early.

Because of natural variations in concentration of water samples, the slowly increasing impact of an anthropogenically induced salt water intrusion is maybe not recognized immediately. Plotting the values within the Valjashko diagram illustrates the chemical water development and supports an early detection of salinization, as can be seen in Figure 6a. For a time series of water samples at monitoring point 2, also small changes in concentration are visualized by an obvious movement towards the sodium chloride end-member (Fig. 6b). Measurements to detect intruding saline water at an early stage should be done in aquifers where potential migration pathways exist, since extended aquitards prevent further upward migration and therefore lead to a delay in salinization: in aquifer 2 concentrations of saline water increase up to one order of magnitude later compared to the aquifer 3 located below (Table 1 and Fig. 6).



Δc_{NaCl} (g/L)	t (a)
0.005	0.35
0.01	0.41
0.02	0.51
0.05	0.66
0.1	0.86
0.2	1.08

initial c_{NaCl} = 0.26 g/L

Δc_{NaCl} (g/L)	t (a)
0.01	2.9
0.02	3.9
0.05	6.2
0.1	9.5
0.2	14.3
0.3	18.4

initial c_{NaCl} = 0.07 g/L

Fig. 6. (a) Valjashko diagram outlines mixing processes of the groundwater types, here exemplarily for scenario F_{10mD} R_{high}; (b) intrusion of saline water at monitoring point 2 appears up to one order of magnitude faster than at monitoring point 3 (c).

4. Conclusions

Salinization of shallow freshwater aquifers as a result of subsurface fluid injection has been quantified by 2D species transport simulations for a prospective storage site in the Northeast German Basin based on a model of 11 km width and 220 m height. An erosional channel and a permeable fault zone are considered as migration pathways towards freshwater aquifers.

The results show that location and degree of salinization are governed by the hydrogeological properties of the two migration pathways. Further, upward displacement of saline water arises along the erosional channel even if the fault is closed. The local groundwater flow influences the distribution of the saltwater mainly in the upper aquifers 1 and 2, where the impact of injection-induced flow is low. The existing drinking water well of the study site is not affected by salinization within the investigated time frame of 20 years injection due to its hydrodynamic position.

The time frame for early warning of freshwater salinization depends on the location of the observation wells. If wells are positioned in a distance of 300 m to the permeable fault zone or the erosion channel in depths of 100 m and 150 m, beginning salinization can be detected already after 0.39 to 0.91 years and 0.3 to 1.32 years, respectively. Hence, an intervention regarding fluid injection is possible before an extensive salinization arises. Further Valjashko diagrams support an early detection of salinization since small changes in concentration can be visualized and indicate changes of the water type.

Acknowledgements

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